Space-Based Searches for Lorentz and CPT Violation [1]

Neil Russell

Physics Department, Northern Michigan University, Marquette, MI 49855, U.S.A.

email: nrussell@nmu.edu

In this proceedings, a summary is presented of recent research investigating ways in which high-precision atomic clocks on the International Space Station could search for violations of Lorentz and CPT symmetry. Space-based searches offer certain experimental advantages over Earth-based experiments investigating these symmetries. The results are based on work published in Physical Review Letters, volume 82, article 090801, 2002.

1. Introduction

This contribution to the proceedings of the 2002 NASA/JPL Workshop on Fundamental Physics in Space summarizes recent research [1] aimed at using atomic clocks and other apparatus on the International Space Station to search for violations of Lorentz and CPT symmetry at the Planck scale. We consider generalities relating to experiments mounted on spacecraft and consider some tests that could be performed using clocks planned for installation on the International Space Station (ISS). This work was done in collaboration with Robert Bluhm, Alan Kostelecký, and Charles Lane.

Lorentz symmetry is a feature of the standard model of particle physics. A considerable body of research exists investigating the possible violation of Lorentz symmetry, however. From the theoretical view, the motivation for this effort lies in discovering new physics beyond the standard model. From the experimental side, the rapidly improving sensitivities of various experiments may reveal previously unresolved effects. Recent theoretical work on Lorentz and CPT symmetry includes the development of a framework that allows for general minuscule violations of these symmetries in the context of particle physics. This framework is known as the standard-model extension [2].

Associated with the standard-model extension is a range of literature discussing a variety of theoretical issues, as well as a growing number of experimental results bounding possible effects. The violation of Lorentz symmetry [3] may arise in the context of string theory, and may be accompanied also by CPT violation [4]. Violation of Lorentz and CPT symmetry has also been discussed in the context of supersymmetry [5], and noncommutative field theory [6]. The standard-model extension is expected to be the low-energy limit of some fundamental underlying theory, and so the violations would most likely be suppressed by ratios involving the low-energy mass and the 10^{19}-GeV Planck mass. The broad applicability of the standard-model extension to all areas of physics is an attractive feature. Among the interesting implications is a possible mechanism for generating the baryon asymmetry in the universe [7]. For the neutral mesons, some bounds on standard-model extension parameters exist for the neutral K and D mesons, and results are anticipated for the neutral B system [8, 9, 10, 11]. The symmetry properties of these meson systems have interesting analogue models in classical mechanics [12]. In the photon sector, data from distant cosmological

[1] From the 2002 NASA/JPL Workshop for Fundamental Physics in Space, Dana Point, CA, May 2002.

sources places stringent bounds on Lorentz symmetry [2, 13, 14]. In the lepton sector, recent results have come from a muonium experiment, and from anomaly-frequency comparisons of oppositely-charged muons at CERN and BNL [15]. Earlier work considered electron-positron comparisons using Penning traps [16]. Impressive results are possible with a spin-polarized torsion pendulum [17].

Of particular relevance here are clock-comparison experiments with atoms and ions [18, 19, 20, 21]. Such experiments can identify spectral lines with resolutions at the Planck scale [22]. The general principle of a clock-comparison experiment is to search for violations of rotational symmetry by monitoring the frequency variations of a Zeeman hyperfine transition as the quantization axis changes direction. Usually, the frequencies of two different clocks are monitored as the laboratory rotates with the Earth. To avoid issues with signals travelling between two different locations, the clocks are co-located. Placing such an experiment in a satellite may produce results slightly better than have been achieved on earth, and this proceedings aims to consider some of the issues associated with this possibility.

2. Clocks and Inertial Frames

Atomic transitions can be measured with great precision and so are suitable candidates for time standards. In conventional physics with constant laboratory conditions, these clock frequencies are constant quantities. However, in the standard-model extension with Lorentz and CPT violation, some Zeeman hyperfine transitions are shifted in frequency [22]. For an experiment operating on such a transition, these shifts are controlled at leading order by parameters denoted in the clock reference frame as $\tilde{b}_3^w$, $\tilde{c}_q^w$, $\tilde{d}_3^w$, $\tilde{g}_d^w$, $\tilde{g}_q^w$. Here, the superscript w is p for the proton, n for the neutron, and e for the electron. These quantities are particular combinations of the basic coefficients a_μ^w, b_μ^w, $c_{\mu\nu}^w$, $d_{\mu\nu}^w$, e_μ^w, f_μ^w, $g_{\lambda\mu\nu}^w$, $H_{\mu\nu}^w$ appearing in the standard-model extension, and are related to expectation values in the underlying fundamental theory. For example,

$$\tilde{b}_3^w = b_3^w - m_w d_{30}^w + m_w g_{120}^w - H_{12}^w \ , \tag{1}$$

where m_w is the mass of the particle of type w and the subscripts are indices defined in a reference frame with the 3 direction defined as the clock quantization axis.

In the case of an Earth-based laboratory, the parameters $\tilde{b}_3^w$, $\tilde{c}_q^w$, $\tilde{d}_3^w$, $\tilde{g}_d^w$, $\tilde{g}_q^w$ are not fixed, but vary in time due to the sidereal rotation of the Earth with period $23\,\mathrm{h}\,56\,\mathrm{min} \simeq 2\pi/\Omega$. The mathematical form of this time dependence can be found by considering the transformation from the laboratory frame containing the clock, with coordinates numbered $(0, 1, 2, 3)$, to a suitable nonrotating frame with coordinates (T, X, Y, Z). Ideally, an inertial nonrotating frame is required, but for practical purposes any frame sufficiently inertial for the desired experimental sensitivity may be selected. Frames associated with the Earth, the Sun, the Milky Way galaxy, or the cosmic microwave background radiation would be possible choices for the inertial frame.

In earlier literature, the nonrelativistic transformation from the clock frame to the nonrotating frame has been considered [22]. In the case of space-based experiments, leading-order relativistic effects are of interest. An Earth-centered choice of reference frame must then be rejected for such relativistic investigations because it is inertial over a limited time scale of perhaps a few days. Frames centered on the Sun, the galaxy, or the microwave background are approximately inertial over thousands of years, and are all acceptable for experiments. The choice of frame must be stated when reporting bounds on components of coefficients of Lorentz violation, since the numerical values will be frame-dependent.

A good choice of reference frame for our purposes is one centered on the Sun. So, we select the spatial origin on the Sun, the $\hat{Z}$ unit vector parallel to the Earth's rotation axis, the $\hat{X}$ unit vector in the equatorial plane pointing at the celestial vernal equinox, and $\hat{Y}$ completing the right-handed system. The origin of the time variable T is taken to be the vernal equinox in the year 2000, using a clock located at the spatial origin. In this system, the Earth orbits about the Sun in a plane tilted at an angle of $\eta \simeq 23^\circ$ relative to the XY plane.

An adequate geometrical description of the orbital configuration can be obtained by approximating the Earth's orbit as a circular trajectory with angular frequency $\Omega_\oplus$ and speed $\beta_\oplus$. In addition, a satellite orbit about the Earth is approximated as circular with angular frequency ω_s and speed β_s. We use ζ to denote the angle between $\hat{Z}$ and the axis of the satellite orbit. We denote by α the right ascension angle of the ascending node of the orbit. In the case of the ISS, α precesses by a few degrees per day.

Time intervals on a clock in a satellite are dilated when seen from the inertial Sun frame. Relative to the Sun-based frame, the clock velocity is $\vec{V}(T) = d\vec{X}/dT$, where the position vector $\vec{X}(T)$ of the clock is determined by positions of the Earth and the spacecraft. This vector $\vec{V}(T)$ is needed to obtain an accurate conversion between the times in the laboratory and in the Sun frame. In principle, effects such as perturbations in this vector and in the gravitational potential should be included in this description. In practice, these corrections may be neglected because the experiments involve comparing two clocks within the same satellite, which are essentially at the same location. In this case, standard relativity predicts identical rates of advance of the clocks. However, in the presence of Lorentz and CPT violation, clocks composed of different atomic species will be differently affected, despite being co-located .

Pertinent issues exist concerning the optimal orientation of the clock quantization axis relative to the geometric configuration of the system. If the clock apparatus is fixed within the satellite, the flight mode of the satellite will determine the clock quantization axis relative to the Sun frame. For this proceedings, we focus on a flight mode with quantization axis tangential to the circular satellite trajectory about the Earth. We choose the clock reference frame with 3 axis parallel to the satellite motion about the Earth, 1 axis pointing towards the center of the Earth, and 2 axis perpendicular to the satellite orbital plane. This configuration would be possible with some clock experiments on the ISS. The results outlined here are specific examples, but we note that other modes of flight and quantization-axis configurations can be handled by the methods discussed here. It is important to note that sensitivity to some components is only possible with specific quantization-axis orientations.

Experiments searching for Lorentz and CPT violation in the context of the standard-model extension are aimed at measuring the tensor-like parameters a^w_μ, b^w_μ, $c^w_{\mu\nu}$, $d^w_{\mu\nu}$, e^w_μ, f^w_μ,

$g^w_{\lambda\mu\nu}$, $H^w_{\mu\nu}$ in our standard solar reference frame. Measurements made in the laboratory frame must be transformed to the Sun-based frame by taking into account the relevant rotation and boost $\vec{V}(T)$. This means that the components of the coefficients for Lorentz violation in the clock frame must be expressed in terms of components in the Sun-based frame. To give an example, the transformation of the component b^w_3 is

$$\begin{aligned} b^w_3 &= b^w_T\{\beta_s - \beta_\oplus[\sin\Omega_\oplus T(\cos\alpha\sin\omega_s\Delta T \\ &\qquad\qquad + \cos\zeta\sin\alpha\cos\omega_s\Delta T) - \cos\eta\cos\Omega_\oplus T \\ &\qquad\qquad \times(\sin\alpha\sin\omega_s\Delta T - \cos\zeta\cos\alpha\cos\omega_s\Delta T) \\ &\qquad\qquad + \sin\eta\cos\Omega_\oplus T\sin\zeta\cos\omega_s\Delta T]\} \\ &\quad - b^w_X(\cos\alpha\sin\omega_s\Delta T + \cos\zeta\sin\alpha\cos\omega_s\Delta T) \\ &\quad - b^w_Y(\sin\alpha\sin\omega_s\Delta T - \cos\zeta\cos\alpha\cos\omega_s\Delta T) \\ &\quad + b^w_Z\sin\zeta\cos\omega_s\Delta T, \end{aligned} \tag{2}$$

where $\Delta T = T - T_0$ is the time interval measured from an agreed reference time T_0. This transformation ignores effects such as the Thomas precession, holding only up to leading order in the velocities. The above result for b^w_3 has to be included with the transformations for the other coefficients to get the full result for the observable parameter $\tilde{b}^w_3$ in the Sun frame. The other coefficients $\tilde{c}^w_q$, $\tilde{d}^w_3$, $\tilde{g}^w_d$, and $\tilde{g}^w_q$ are found by a similar method. The expressions that result depend on combinations of basic coefficients for Lorentz and CPT violation, on trigonometric functions of various angles, on frequency-time products, on $\beta_\oplus$, and on β_s.

3. Signal Features

Satellite-based experiments offer accessibility to all the spatial components of the basic coefficients for Lorentz and CPT violation. This eliminates a major constraint due to the fixed rotation axis for Earth-based experiments, preventing sensitivity to various spatial components. For instance, ground-based experiments sensitive to the laboratory-frame parameter $\tilde{b}^w_3$ would in turn be sensitive only to the nonrotating-frame components $\tilde{b}^w_X$, $\tilde{b}^w_Y$. They can therefore bound only a limited subset of components of b^w_μ, $d^w_{\mu\nu}$, $g^w_{\lambda\mu\nu}$, $H^w_{\mu\nu}$. This limitation would be overcome by a satellite platform. In the case of most satellites, the orbital axis is tilted relative to the Earth's rotation axis, and the orientation of this orbital axis precesses about the steady axis of the Earth. This precession makes the other spatial directions accessible to satellite tests.

Another attractive feature of the satellite platform for experiments is the relatively short orbital period. Since the satellite orbital period $2\pi/\omega_s$ for low-altitude satellites is much less than a sidereal day, data can be collected in a substantially reduced period. In the case of the ISS, the 92-minute orbital period translates into a data-collection period approximately 16 times shorter than on Earth, where the orbital period is about 24 hours. This could contribute to better results since it would reduce the sensitivity loss due to clock instabilities over time. One interesting advantage of this reduced experimental time is due to the fact that the Earth's velocity vector would remain essentially constant over the experimental duration. This makes it possible to analyze the leading-order relativistic effects due to the speed $\beta_\oplus \simeq 1 \times 10^{-4}$ of the Earth relative to the Sun. Such tests are not possible with ground-based experiments, because they require several months of data, during which time the velocity of the Earth changes significantly. The analysis would be considerably simplified by the fact that the Earth could be regarded as an inertial reference frame. Direct extraction of leading-order relativistic effects would be possible.

The observations above show that many types of Lorentz and CPT violation that are unconstrained to date would be accessible in space-based experiments. As an example, consider a clock-comparison experiment with sensitivity to the observable $\tilde{b}_3^w$ for particle species w. In the Sun-based frame and for each w, this observable is a linear combination of the basic coefficients b_μ^w, $d_{\mu\nu}^w$, $g_{\lambda\mu\nu}^w$, $H_{\mu\nu}^w$ for Lorentz violation, numbering 35 independent observable components if the effect of field redefinitions is allowed for. Whereas a conventional ground-based experiment is sensitive to 8 of these, the same type of experiment mounted on a space platform would be sensitive to all 35. Another approach to overcoming constraints on accessible coefficients would be to construct a suitably-oriented rotating base for a ground-based experiment. This option is not pursued here, since the current work is aimed at understanding sensitivities of experiments planned for the ISS.

For ground-based experiments, some relativistic Lorentz and CPT coefficients are suppressed by the boost factor of the Earth, $\beta_\oplus$. In comparison, space-based clock-comparison experiments would also be sensitive to first-order relativistic effects proportional to the boost factor of the satellite, β_s. In Earth-based experiments, investigating the corresponding effects of the lab motion relative to the Earth's center would be impractical. Such effects would also be further suppressed by Ω/ω_s, which is about 6×10^{-2} in the case of the ISS.

A somewhat unexpected effect exists among the order-β_s corrections. It is found that in space-based experiments a dipole shift can lead to a potentially detectable signal with frequency $2\omega_s$. This is not seen in the nonrelativistic analysis of Earth-based clock-comparison experiments, where signals with the double frequency 2Ω occur only for quadrupole shifts. To better understand this, consider the parameter $\tilde{b}_3^w$, which nonrelativistically is the third component of a vector and would lead only to a signal with frequency ω_s. This parameter $\tilde{b}_3^w$ contains the component d_{03}, however, which in a relativistic approach behaves like a two-tensor at leading order in β_s, and would therefore lead to a signal at frequency $2\omega_s$. We give an example: when the Earth is near the northern-summer solstice, $\tilde{b}_3^w$ in the Sun-based frame has a double-frequency term that goes like $\cos(2\omega_s \Delta T)$ with coefficient C_2 containing the following spatial components of $d_{\mu\nu}^w$:

$$
\begin{aligned}
C_2 \quad \supset \quad & \beta_s \frac{m}{8}[\cos 2\alpha(3+\cos 2\zeta)(d_{XX}^w - d_{YY}^w) \\
& +(1-\cos 2\zeta)(d_{XX}^w + d_{YY}^w - 2d_{ZZ}^w) \\
& -2\sin 2\zeta(\cos\alpha\,(d_{YZ}^w + d_{ZY}^w) - \sin\alpha\,(d_{ZX}^w + d_{XZ}^w)) \\
& +(3+\cos 2\zeta)\sin 2\alpha\,(d_{XY}^w + d_{YX}^w)]. \qquad (3)
\end{aligned}
$$

This shows that all observable spatial components of $d_{\mu\nu}^w$could be accessed through appropriate monitoring of the 2ω frequency.

3. Experiments on Earth Satellites

The ISS will house a number of high-precision clocks and other oscillators capable of testing fundamental physics in the coming years. Instruments slated for installation include H masers, laser-cooled Cs and Rb clocks, and superconducting microwave cavity oscillators [23, 24, 25, 26]. Among the experimental advantages of the ISS are the orbital parameters $\beta_s \simeq 3 \times 10^{-5}$ and $\zeta \simeq 52^\circ$, which correspond to a speed and orbital plane outside the scope of Earth-based experiments. In addition, experiments on the ISS would be conducted in a microgravity environment with reduced environmental disturbances, and these features are expected to lead to sensitivity gains compared with ground-based clocks. The analysis presented in this proceedings is valid for tests with all these clocks, but not for the oscillators, which are discussed elsewhere [14].

In our discussion, we consider a canonical configuration with a signal clock being compared to a co-located reference clock. The signal clock is sensitive to leading-order Lorentz and CPT violation, while the reference clock, for example an H maser tuned to its clock transition $|1,0\rangle \to |0,0\rangle$, is insensitive to such effects.

Hydrogen Masers

A hydrogen maser operating on the transition $|1,\pm 1\rangle \to |1,0\rangle$ would be one possible signal clock. A recent ground-based experiment used a double-resonance technique to monitor this transition frequency [21], which is sensitive to the parameters $\tilde{b}_3^p$ and $\tilde{b}_3^e$ in the clock frame. The sensitivity to relatively clean parameter combinations is a consequence of the simplicity of the hydrogen system as compared with atoms such as Rb or Cs used in atomic clocks. Mounting this experiment on the ISS would mean that an experimental run of only about a day would suffice to obtain data roughly equivalent to four months of data taken on Earth with a similar experiment on a fixed base. For both $w = e$ and $w = p$, all spatial components of b_μ^w, $m_w d_{\mu\nu}^w$, $m_w g_{\lambda\mu\nu}^w$, $H_{\mu\nu}^w$ could be sampled by exploiting the orbital inclination ($\zeta \neq 0$) and by repeating the experiment at a later time when orbital precession corresponds to a significantly different value of α. Making the assumption of a 500 μHz sensitivity, equalling that attained in Earth-based experiments, several presently unbounded components would be probed at the level of about 10^{-27} GeV, and others at about 10^{-23} GeV. We also estimate that cleaner bounds on certain spatial components of $m_w d_{\mu\nu}^w$, $m_w g_{\lambda\mu\nu}^w$at the level of about 10^{-23} GeV could be obtained by searching for a signal at the double frequency $2\omega_s$. In all, about 50 components of coefficients for Lorentz and CPT violation that are currently unbounded could be tested at the Planck scale.

Cesium Clocks

In the case of a laser-cooled ^{133}Cs clock, a reference frequency could be provided by the usual clock transition $|4,0\rangle \to |3,0\rangle$, which is insensitive to Lorentz and CPT violation. A Zeeman hyperfine transition such as $|4,4\rangle \to |4,3\rangle$ would be needed to provide a signal. Since ^{133}Cs has an unpaired electron, this atom has sensitivity to electron parameters similar to that of the H maser. In the Schmidt model, the ^{133}Cs nucleus is a proton with angular momentum

7/2, giving sensitivity to all clock-frame parameters $\tilde{b}_3^p$, $\tilde{c}_q^p$, $\tilde{d}_3^p$, $\tilde{g}_d^p$, $\tilde{g}_q^p$, and yielding both dipole and quadrupole shifts. We note that components tested would include $c_{\mu\nu}^p$. Repeating results achieved in an Earth-based experiment would imply a sensitivity level of about 50 μHz [19] on the $|4,4\rangle \to |4,3\rangle$ transition. A similar experiment on the ISS would potentially run for a period reduced by a factor of 16. Furthermore, measurements of the double-frequency signal $2\omega_s$ would probe the spatial components of $c_{\mu\nu}^p$ at the 10^{-25} level, and other components at about the 10^{-21} level. We estimate that about 60 components of coefficients for Lorentz and CPT violation would be accessible at the Planck-scale.

Rubidium Clocks

Experiments with ^{87}Rb are similar in many ways to ones with ^{133}Cs. The clock transition $|2,0\rangle \to |1,0\rangle$, is insensitive to Lorentz and CPT violation, and so is a suitable reference signal. A Zeeman hyperfine transition such as $|2,1\rangle \to |2,0\rangle$ is a potential signal transition. Like H and ^{133}Cs, ^{87}Rb has an unpaired electron, an is therefore sensitive to similar electron parameters as discussed for those systems. The sensitivity to proton parameters is also similar to that for ^{133}Cs, up to factors of order unity, because the Schmidt nucleon for ^{87}Rb is a proton with angular momentum 3/2. An advantage from the theoretical viewpoint is the magic neutron number, which aids in calculational reliability and leads to cleaner results [22]. A considerable range of Lorentz and CPT bounds could be envisaged for ^{87}Rb with ideas along these lines.

Other Spacecraft

Lorentz and CPT tests could be done with on a variety of space platforms. Missions where the speeds of the craft with respect to the Sun are larger than the speed β_s for Earth-orbiting satellites are of particular interest. One possibility is the proposed SpaceTime [27] experiment, which would attain $\beta \simeq 10^{-3}$ on a trajectory sweeping from Jupiter in towards the Sun. This mission will fly $^{111}Cd^+$, $^{199}Hg^+$, and $^{171}Yb^+$ ion clocks in a craft rotating several times per minute. This rotation rate would offer the possibility of gathering data for a Lorentz and CPT test in as little as 15 minutes. The clock transitions $|1,0\rangle \to |0,0\rangle$ are insensitive to Lorentz and CPT violation for all three clocks, and so could be used as reference signals. Zeeman hyperfine transitions such as $|1,1\rangle \to |1,0\rangle$ are sensitive to Lorentz- and CPT-violating effects in the standard-model extension and could provide signal clocks. In the context of the Schmidt model, all three clocks are sensitive to the neutron parameters $\tilde{b}_3^n$, $\tilde{d}_3^n$, $\tilde{g}_d^n$ in the clock frame. Such experiments would be of particular interest because none of the above neutron parameters can be probed with the proposed ISS experiments. Several tests for Lorentz and CPT violation would be possible by seeking variations in the signal-clock outputs at the spacecraft rotation frequency ω_{ST} and also at $2\omega_{ST}$. Experiments in this category would gain an order of magnitude advantage over Earth-based or Earth-orbit experiments because of their larger boost factors.

4. Discussion

The standard-model extension is a microscopic theory predicting possible minuscule Lorentz-and CPT-violating effects in physical systems. Some of the experimental challenges facing measurements of such effects can be overcome by mounting experiments on satellites orbiting the Earth. In particular, atomic clocks planned for the International Space Station will be able to exploit the relatively high rotation rates of the ISS as well as the relatively high speed relative to the Earth to gain sensitivity to relativistic effects within the context of the standard-model extension. Other experiments of interest in this context include satellite-mounted microwave oscillators.

5. Acknowledgments

I thank Robert Bluhm, Alan Kostelecký, and Chuck Lane for their collaboration on this work. This work was partially supported by a grant from Northern Michigan University.

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